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# A new quasi-invariant parameter characterizing the postural alignment of young asymptomatic adults

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## Abstract

**Purpose** Our study aims to describe the postural alignment of young asymptomatic subjects from head to feet from bi-planar standing full-body X-rays, providing database to compare to aging adults. Novelty resides in the inclusion of the head and lower limbs in the erected posture's analysis.

**Methods** For 69 young asymptomatic subjects (18–40 years old) 3D reconstructions of the head, spine, pelvis and lower limbs segments were performed from bi-planar full-body X-rays. Usual studied spinal, pelvic and lower limbs' parameters were computed in 3D, sagittal and frontal planes of the patient. Relationships between these parameters were investigated. Inclinations of different lines were studied to characterize the erected posture.

**Results** Values found for spinal curvatures, pelvic parameters and lower limbs geometrical parameters agreed with the literature: thoracic kyphosis, lumbar lordosis, pelvic incidence, pelvic tilt and sagittal vertical axis were respectively in average of 26.9° (SD 7.2°), 30.5° (SD 7.5°), 51.0° (SD 9.4°), 11.1° (SD 5.6°) and –8.9 mm (SD

21.6 mm). The angle between the vertical and the line joining the most superior point of dentiform apophyse of C2 (OD) and the center of the bi-coxofemoral axis (HA) was the less variable one (SD 1.6°).

**Conclusions** This study on 3D postural alignment reports the geometry of the spine, pelvis and lower limbs, of the young asymptomatic adult. The less variable angle is the one of the line OD–HA with the vertical, highlighting the vertical alignment of the head above the pelvis. This study provides a basis for future comparisons when investigating aging populations.

**Keywords** Skeleton's postural alignment · 3D · Asymptomatic young adults · Head to feet · Spinal alignment

## Introduction

Dubousset first introduced the concept of the “conus of economy” describing the economic standing posture [1]. Failure to maintain the center of gravity in this conus would trigger compensatory mechanisms to restore a stable posture. Postural alignment is maintained to stay in this “conus of economy”: alignment of all segments above the pelvis (torso and head) is needed to provide the best posture at the least energy expense. Particularly, keeping the head aligned with the whole body is important to provide horizontal gaze, but also accurate sensory inputs (i.e. inner ear). Adding that the head weight is approximately 4 to 5 kg [2], its global position in space appears of prior importance when considering posture and balance.

However, during aging, degradation of the musculo-skeletal system, due to disc degeneration, osteoporosis and loss of muscular volume, contributes to the degradation of

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postural alignment, leading to potential severe osteoarticular damages [3]. In addition, postural malalignment increases the risk of loss of balance and fall that are associated to societal costs (for example, US\$ 17,483 mean cost of hospitalization for fall-related injury in the US [4]). To maintain this postural alignment, different strategies, involving the whole body from head to feet, are followed depending on the subject's functional capabilities. In an effort to maintain the alignment of different body's segments (head, torso, pelvis, lower limbs) objective, young subjects have the capacity to regulate their spino-pelvic alignment by fine-tuning the curvature of their spine and adjusting the orientation of their pelvis. In comparison, it has been demonstrated that older subjects recruit preferably mechanisms of compensation at the pelvis and lower limbs levels [5].

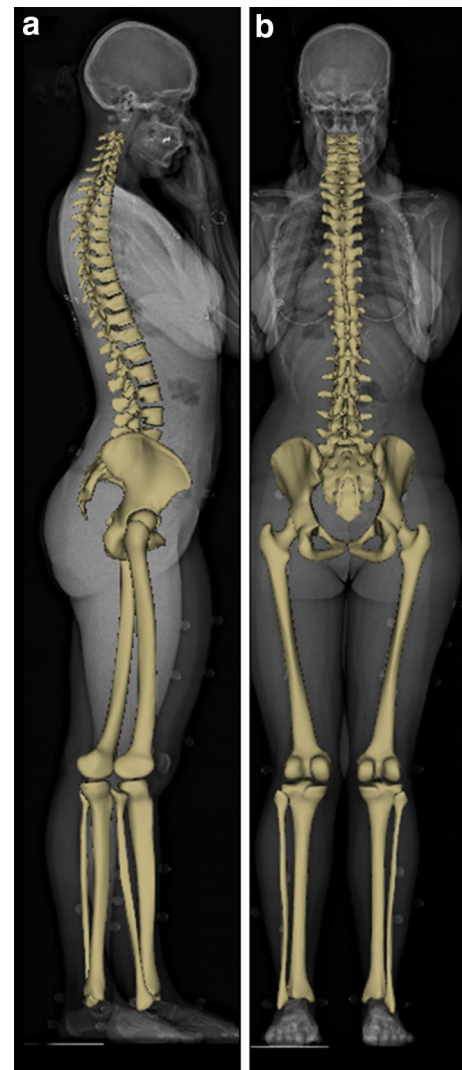
Evaluation of the posture has been made in the past by studying the spine and pelvis on sagittal X-rays [6–9]. To our knowledge, only two studies reported the alignment of the head with the rest of the body, stating that the inclination of the head compared to the pelvis could be a good indication of the postural trouble [10, 11] while others only focused on the alignment of C7 with the rest of the spine and pelvis [12, 13]. Previous clinical studies included the lower limbs, massively in 2D (not relevant for torsion values for example) [14]. However reference values, in 2D and 3D, of the complete global alignment of the normal young adult from a whole body (head to feet) exam are not yet available.

The aim of the current study was to study the postural alignment of young asymptomatic subject including head, spine, pelvis and lower limbs, in 2D and 3D. Possible invariant parameters of the young adults' posture were investigated.

## Materials and methods

### Volunteers and data selection

69 volunteers (32 male and 37 female) were retrospectively included in the study: bi-planar X-rays radiographies were obtained between February 2007 and July 2014 after approval by the Ethics Committee (Comité de Protection des Personnes CPP N°06036) and written informed consent. Bi-planar X-rays were obtained with the EOS system, a low-dose system allowing acquiring simultaneously radiographies in the sagittal and coronal planes of the patient (with two sources at 90°), from head to feet [15]. Inclusion of the EOS radiographies in the study required total visibility of the lower limbs bones and vertebrae on both views. Among exclusion criteria were previous musculo-skeletal surgery, previous surgery or pathology concerning the visual and/or the hearing system(s). Patients

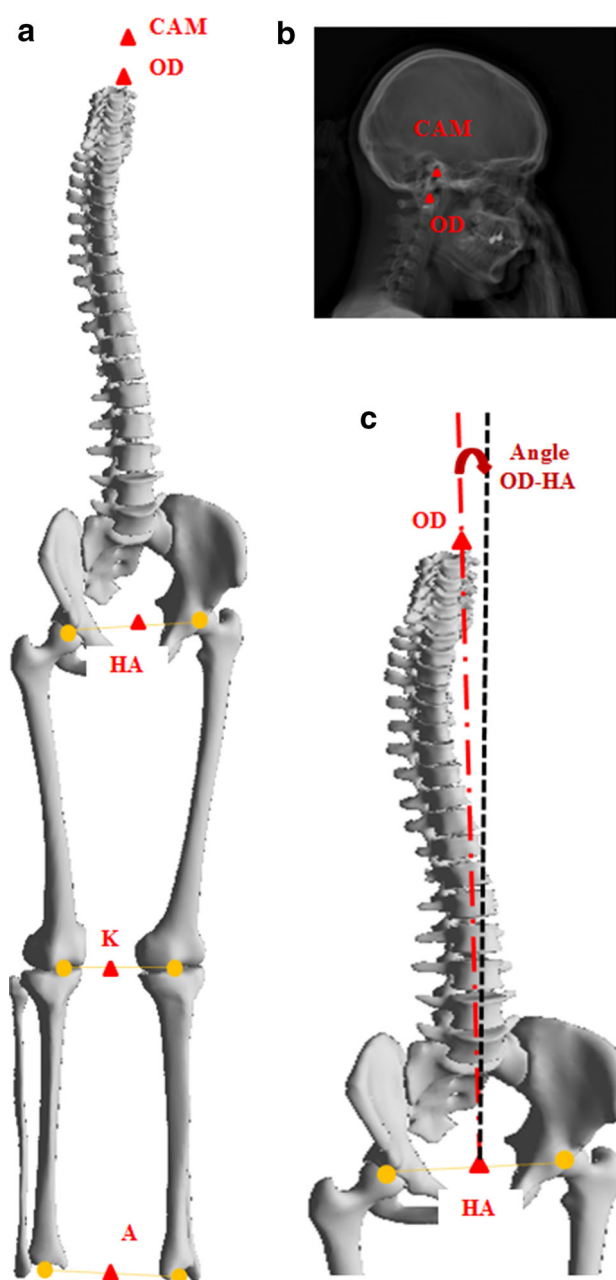


**Fig. 1** Bi-planar radiographies with 3D model of the spine (C3 to L5), pelvis and lower limbs **a** sagittal view, **b** coronal view

were asked to stand up in the standardized free standing position, adapted from Faro et al. [16], with the hands resting on the mandibles (SRS modified free standing position) and with shifted feet positioned as described by Chaïbi et al. [17] (Fig. 1).

### Imaging data processing

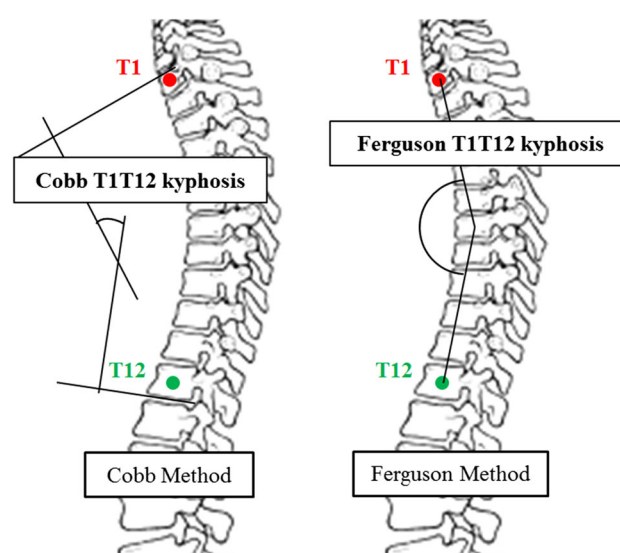
From bi-planar X-rays, a 3D patient-specific model including the spine [from C3 to L5, with addition of the most superior point of dentiform apophyse of C2 (OD)], the pelvis, and the lower limbs; was obtained using validated reconstructions techniques [17–20] (Fig. 2a). In addition, as described by Steffen et al. [10], when visible, two stereo-corresponding points localizing the acoustic meati were digitized to each reconstruction to compute their center (CAM) (Fig. 2b).



**Fig. 2** **a** 3D model of the spine (C3 to L5), pelvis and lower limbs: identification of the center of the acoustic meati (CAM), the most superior point of dentiform apophyse of C2 (OD), the centers of T1 and T9 vertebral bodies (T1 and T9), the center of the sacral plate (S1), the center of the bi-coxofemoral axis (HA), the middle of both knees points (K), and the middle of both ankles (A). **b** Detailed identification of CAM and OD points on the sagittal radiography. **c** Example of OD-HA parameter: angle with the vertical of the line joining the points OD and HA

## Studied parameters

All the parameters were calculated in the anatomo-gravital frame, which is the patient frame: the frontal plane is the vertical plane going through both acetabulum centers',



**Fig. 3** Differences between Cobb method and Ferguson method to calculate spinal curvatures (example of kyphosis T1T12)

transversal and sagittal planes are orthogonal to the frontal plane. The origin of the frame is the center of the bi-coxofemoral segment (point named HA). Parameters' definitions are detailed in Tables 2 and 3.

Pelvic (pelvic incidence, pelvic tilt and sacral slope) and lower limbs parameters were calculated from 3D reconstruction. Spinal curvatures (cervical lordosis, thoracic kyphosis and lumbar lordosis) were calculated using both Cobb and Ferguson methods (Fig. 3).

Angles of the vertical with specific lines going through various landmarks (Fig. 2) were also calculated.

Two global alignment lines were defined, searching for the most invariant one among subjects (defined as the one with the smallest standard deviation). The first line was defined as the line that best fits (in the least square sense), the following anatomical landmarks: middle of the centers of acoustic meati (CAM), the most superior point of dentiform apophyse of C2 (OD), all the vertebral bodies' center from C3 to L5, center of the sacral plate (S1) and middle of the centers of each acetabulum (HA). The second line was defined similarly without including the CAM point in the landmarks considered.

As proposed by Steffen et al. [10], offsets of the following points were calculated CAM, T1, T4, T9, L3, and S1. We also considered the most superior point of dentiform apophyse of C2 (OD), the center of the knees (K) as the middle points of right and left middle point between condyles' centers and tibial plates' centers. The center of ankles (A) was also considered as the middle point of right and left centers of bimalleolar axis. Figure 2a presents all the points considered for offsets analysis. The offsets were calculated, in 3D, and in both directions of the transversal

plane (postero-anterior and medio-lateral), as the distance between these points and the vertical going through HA.

The reliability of each point was already described elsewhere except for the OD location [19]. For this parameter, two operators digitized the points two times for 12 patients on two distinct set of radiographies for each (48 repetitions per operator): 95 % confidence interval was respectively of 2.0 mm for X, antero-posterior direction; of 1.2 mm for Y, medio-lateral direction; and of 2.2 mm for Z, superior direction.

## Statistical analysis

A paired-sample *t* test was run on lower limbs' parameters to find if there was any statistical difference between right and left sides [21].

A Lilliefors normality test [22] was run on all parameters. Correlations were searched for using pairwise Spearman correlations (significance level was set at 0.05).

## Results

### Description of the sample

Mean age was 26.3 years old [standard deviation (SD): 4.7 years old] (Table 1). The acoustic meati were not visible on 8 EOS exams out of the 69. Over all parameters used to study correlations, 13 were found to not be drawn from a normal distribution (Table 2). As these parameters' distributions were found, by the operators, to be close to a bell-shape, means and SD were reported for all parameters (Tables 2, 3).

In average, pelvic incidence, pelvic tilt, and sacral slope were respectively of 51.0° (SD 9.4°), 11.1° (SD 5.6°) and 40.5° (SD 8.7°). As for the spine curvatures, the 3D T1T12 thoracic kyphosis was in average of 26.9° (SD 7.2°) versus 30.5° (SD 7.5°) for the L1S1 lumbar lordosis.

### Analysis of the least variant parameter(s)

The inclinations, with the vertical, of the line joining CAM to HA and of the line joining OD to HA had the lowest

variation with a SD respectively of 1.7° and of 1.6° and were the closest to the vertical: mean inclination of 2.9° for both. In comparison, means (SD) of C7–HA, T1–HA and T9–HA were respectively of 4.3° (1.9°); 5.5° (2.0°) and 10.6° (2.8°).

As for the lines that could possibly represent the global inclination of the spine, the less variable inclinations between subjects were when using the two following combinations of points for the calculation of the least-squared line: (1) CAM, OD, centers of C3 to L5 vertebral bodies (line called Incl\_1), and S1; (2) OD, centers of C3 to L5 vertebral bodies, and S1 (line called Incl\_2). Values are reported in Table 3.

When considering the offsets between HA and different plumbines (Fig. 4) dropped from the specific anatomical landmarks (CAM, OD, T1, T4, T9, L3, S1, K, A), the average distances ranged from 70.3 to 10.7 mm posterior to HA ( $SD_{\max} = 24.1$  mm) and from 5.1 mm medial to 2.3 mm lateral to HA ( $SD_{\max} = 14.2$  mm). The distance in the transverse plane ranged from 17.9 to 71.5 mm ( $SD_{\max} = 21.2$  mm). The center of the sacral plate S1, versus HA, presented the lowest variable offset across subjects, in the transverse plane (mean 20.9 mm; SD 9.4 mm). On average, the knee's center and ankles' center were posterior to HA in average less than 6 cm ( $SD < 2$  cm) and were lateral to HA in average less than 1 cm ( $SD < 1.5$  cm).

## Statistical analysis

As, the paired-sample *t* tests revealed that specific parameters (Table 2) presented no statistical differences between both sides, the value kept for analysis was the mean of the right and left values.

Cobb versus Ferguson relationship for spinal curvatures was:  $Cobb_{\text{sag}} = 1.90 \times Ferguson_{\text{sag}} - 2.34$  ( $R^2 = 0.96$ ,  $p$  value  $< 0.05$ ). The pairwise correlations found to be significant ( $p$  value  $< 0.05$ ) are the following ones: L1S1 lordosis with sacral slope ( $R^2 = 0.87$ ), with pelvic incidence ( $R^2 = 0.62$ ), and with thoracic kyphosis (T4T12:  $R^2 = 0.48$ ; T1T12:  $R^2 = 0.36$ ); overhang of S1 with pelvic tilt ( $R^2 = 0.97$ ). No significant correlation was found between spinal and lower limbs parameters.

## Discussion

Erected posture of 69 young asymptomatic adults was described from head to feet in 3D and 2D. If, compensatory mechanisms of the pelvis and lower limbs have been documented in the literature, few have been reported for the cervical level: studying the skeleton postural alignment from head to feet allows for a complete view of the

**Table 1** Demographic data of the volunteers who participated in the study

|                        | Age (years) <sup>a</sup> | BMI (kg/m <sup>2</sup> ) <sup>a</sup> |
|------------------------|--------------------------|---------------------------------------|
| Mean                   | 26.3                     | 22.4                                  |
| 1 × standard deviation | 4.7                      | 3.1                                   |
| Min                    | 20.1                     | 16.6                                  |
| Max                    | 39.7                     | 33.2                                  |

<sup>a</sup> Means that the parameter was not found to be drawn from a normal distribution



**Table 2** Reference values for pelvic and lower limbs parameters: Mean (SD)

| Abbreviation            | Name  | Mean (1 × SD)   |                 |
|-------------------------|---|-----------------|-----------------|
| PI                      | Pelvic incidence (°)  | 51.0 (9.4)      |                 |
| SS                      | Sacral slope (°)  | 40.5 (8.7)      |                 |
| PT                      | Pelvic tilt (°)   | 11.1 (5.6)      |                 |
| S1 <sub>ov</sub>        | Overhang of S1 (postero-anterior distance between S1 and HA) (mm)   | −19.6 (10.2)    |                 |
| SVA                     | Sagittal vertical axis (postero-anterior distance between C7 and <sup>post-sup</sup> S1) (mm)                                       | −8.9 (21.6)     |                 |
| TPA                     | T1 pelvic angle (angle between line T1 to HA and line S1 to HA) (°)   | 5.3 (5.7)       |                 |
| PR <sup>a</sup>         | Pelvic rotation (angle between the frontal plane of the acquisition system and the frontal plane of the anatomo-gravital frame) (°) | 3.2 (2.5)       |                 |
| PO                      | Pelvic obliquity (angle between the bi-coxofemoral axis and its projection on the horizontal plane) (°)                             | −0.3 (2.5)      |                 |
| ^Cov <sub>ext</sub>     | External coverture angle (°)  | R: 29.6 (5.6)   | L: 29.8 (5.3)   |
| ^Cov%                   | Acetabular coverage (%) [23]  | R: 46.5 (3.5)   | L: 46.0 (3.5)   |
| ^Incl <sub>acetab</sub> | Acetabular inclination (°)  | R: 34.1 (3.4)   | L: 33.8 (2.9)   |
| ^Abd <sub>acetab</sub>  | Acetabular abduction (°)  | R: 57.4 (4.4)   | L: 57.0 (3.9)   |
| Antev <sub>acetab</sub> | Acetabular anteversion (°)  | R: 15.5 (3.5)   | L: 16.7 (3.6)   |
| HKS <sup>a</sup>        | Hip–knee centers–femoral shaft angle (°)  | R: 5.5 (1.3)    | L: 5.2 (1.5)    |
| ^TMA                    | Tibial mechanical angle (°)   | R: 87.2 (2.2)   | L: 87.4 (2.0)   |
| ^FMA                    | Femoral mechanical angle (°)  | R: 92.9 (1.7)   | L: 92.6 (2.2)   |
| ^FT                     | Femoral torsion (°)   | R: 12.9 (9.6)   | L: 13.8 (10.8)  |
| ^TT                     | Tibial torsion (°)  | R: 37.1 (6.0)   | L: 35.9 (6.7)   |
| L <sub>F</sub>          | Femoral length (mm)   | R: 426.4 (24.6) | L: 427.5 (24.4) |
| ^L <sub>T</sub>         | Tibial length (mm)  | R: 368.0 (21.9) | L: 368.3 (22.0) |
| L <sub>Tot</sub>        | Lower limb length (mm)  | R: 798.9 (45.6) | L: 800.2 (45.9) |
| ^FTR <sup>a</sup>       | Femoro–tibial rotation (°)  | R: 6.3 (3.9)    | L: 6.6 (5.7)    |
| ^FTMA <sup>a</sup>      | Femoro–tibial mechanical angle (°) (also called HKA)  | R: 174.7 (3.1)  | L: 174.9 (2.6)  |
| ^FNSA                   | Femoral neck shaft angle (°)  | R: 128.3 (4.4)  | L: 128.0 (3.7)  |
| ^FO                     | Femoral offset (3D distance between the center of femoral head and the proximal diaphyseal axis) (mm)                               | R: 40.1 (5.5)   | L: 40.6 (4.2)   |

S1 centre of sacral plate, HA middle of the centers of each acetabulum, C7 center of vertebral body of C7, T1 center of vertebral body of T1, <sup>post-sup</sup>S1 most posterior point of the superior plate of S1, R (L) right (left) side

<sup>^</sup> Means that for the correlation study, the values were averaged between right and left sides (as no statistical differences were reported by the paired *t* test ran)

<sup>a</sup> Means that the parameter was not found to be drawn from a normal distribution

possible compensatory mechanisms. For example, Sugrue et al. is one study of the few to include points at the head level (cranial center of mass of the head and C2) [11]. Overall, our findings match the ones previously reported in the literature, with new information regarding the global postural alignment from head to feet, and in particular the position of the head relative to the pelvis.

### Spinal and pelvic parameters

Agreement with the literature was found for the hip joints' parameters (Cov%, Abd<sub>acetab</sub>, Antev<sub>acetab</sub>) [14, 23], and for spinal and pelvic parameters [6–9, 17, 24, 25], particularly with the studies conducted by Vialle et al. [8] and by Schwab et al. [25].

The correlations found between spinal curvatures and pelvic parameters are similar to the correlations reported in the literature [6–9, 24]. In particular, Vialle et al. found a strong correlation between the L1L5 lordosis and the sacral slope ( $R^2 = 0.76$ ) and a strong correlation between the L1L5 lordosis and the pelvic incidence ( $R^2 = 0.68$ ) [8]. These correlations highlight the influence of the morphology of the pelvis on the lumbar spinal curvature. As for Cobb versus Ferguson values, the relationship found is consistent with the literature [26].

### Lower limbs parameters

For the lower limbs geometrical parameters (HKS, ^TMA, ^FMA, ^FT, ^TT, L<sub>F</sub>, ^L<sub>T</sub>, L<sub>Tot</sub>, ^FTR, ^FTMA, ^FNSA,

**Table 3** Reference values for spinal parameters and inclinations in 3D/sagittal plane/frontal plane: mean (SD)

| Abbreviation        | Description of the line   | 3D                             | Frontal plane                      | Sagittal plane               |
|---------------------|---|--------------------------------|------------------------------------|------------------------------|
| $L_{C3-C7}^a$       | C3–C7 lordosis (°) # 3.7 (0.1)  | 8.6 (4.5)                      | 2.6 (5.2)                          | −0.9 (8.5)                   |
| $K_{T1-T12}^a$      | T1–T12 kyphosis (°) # 49.0 (13.0)   | 26.9 (7.2)                     | −1.1 (5.4)                         | 26.7 (7.3)                   |
| $K_{T4-T12}^a$      | T4–T12 lordosis (°) # 35.1 (11.5)   | 19.2 (6.1)                     | 1.5 (5.4)                          | 18.6 (6.6)                   |
| $L_{L1-L5}^a$       | L1–L5 lordosis (°) # −46.4 (11.9)   | 21.8 (5.9)                     | −3.5 (6.6)                         | −20.7 (5.6)                  |
| $L_{L1-S1}^a$       | L1–S1 lordosis (°) # −57.6 (12.8)   | 30.5 (7.5)                     | 0.4 (10.1)                         | −30.1 (7.6)                  |
| $A_{Pelvis-Fem}$    | Angle between the bi-coxofemoral axis and the bi-condylar axis (°)  | R: 16.4 (8.4)<br>L: 15.4 (7.7) | R: 38.3 (175.0)<br>L: 74.2 (162.8) | –                            |
| Incl_1              | Global Inclination: Angle between the vertical and the line that best fits: CAM, OD, all the vertebral body' centers from C3 to L5, and S1 (°) <sup>b</sup> | 3.1 (1.9)                      | −0.5 (1.1)                         | −2.3 (2.6)                   |
| Incl_2              | Global Inclination: Angle between the vertical and the line that best fits: OD, all the vertebral body' centers from C3 to L5, and S1 (°) <sup>b</sup>      | 3.5 (2.1)                      | −0.5 (1.3)                         | −2.8 (2.7)                   |
| CAM–HA <sup>a</sup> | Angle between the vertical and the line that connects CAM to HA (°)   | 2.9 (1.7)                      | −0.3 (1.0)                         | −2.4 (2.1)                   |
| OD–HA               | Angle between the vertical and the line that connects OD to HA (°)  | 2.9 (1.6)                      | −0.4 (1.2)                         | −2.3 (2.0)                   |
| C7–HA               | Angle between the vertical and the line that connects C7 to HA (°)  | 4.3 (1.9)                      | −0.2 (1.4)                         | −4.0 (2.1)                   |
| CAM–C7              | Angle between the vertical and the line that connects CAM to C7 (°)   | 6.8 (4.2)                      | −1.0 (2.7)                         | 4.1 (6.3)                    |
| OD–C7 <sup>a</sup>  | Angle between the vertical and the line that connects OD to C7 (°)  | 8.0 (4.5)                      | −1.7 (3.4)                         | 5.6 (6.3)                    |
| T1–HA               | Angle between the vertical and the line that connects T1 to HA (°)  | 5.5 (2.0)                      | −0.1 (1.4)                         | −5.3 (2.1)                   |
| T9–HA               | Angle between the vertical and the line that connects T9 to HA. (°)   | 10.6 (2.8)                     | 0.1 (1.7)                          | −10.4 (2.8)                  |
| T1–S1               | Angle between the vertical and the line that connects T1 to S1 (°)  | 4.5 (2.2)                      | −0.2 (1.4)                         | −4.1 (2.7)                   |
| FI <sup>a</sup>     | Femoral inclination (angle of the femoral mechanical axis with the vertical) (°)  | R: 6.3 (3.3)<br>L: 8.3 (3.5)   | R: −0.7 (1.9)<br>L: 0.6 (1.9)      | R: 5.7 (3.8)<br>L: 8.0 (3.6) |
| TI                  | Tibial inclination (angle of the tibial mechanical axis with the vertical) (°)  | R: 4.5 (2.0)<br>L: 5.0 (2.7)   | R: −2.5 (2.2)<br>L: 2.3 (2.0)      | R: 1.4 (3.4)<br>L: 3.6 (3.3) |

For the spinal curvatures, the values in the second column following the # symbol are the values computed with the Cobb method. *R* (*L*) right (left) side

*CAM* middle of the points describing the acoustic meati, *OD* most superior point of dentiform apophyse of C2, *C7/T1/HA/S1*<sup>post-sup</sup> *S1* see legend of Table 2, *T4* (*T9*) center of vertebral body of T4 (*T9*)

<sup>a</sup> means the parameter that was not found to be drawn from a normal distribution and <sup>b</sup> means in the least square sense

FO), the values found match values reported in studies using computer tomography in the supine position and in studies evaluating lower limbs' geometry on 3D model build from bi-planar radiographies [17, 27].

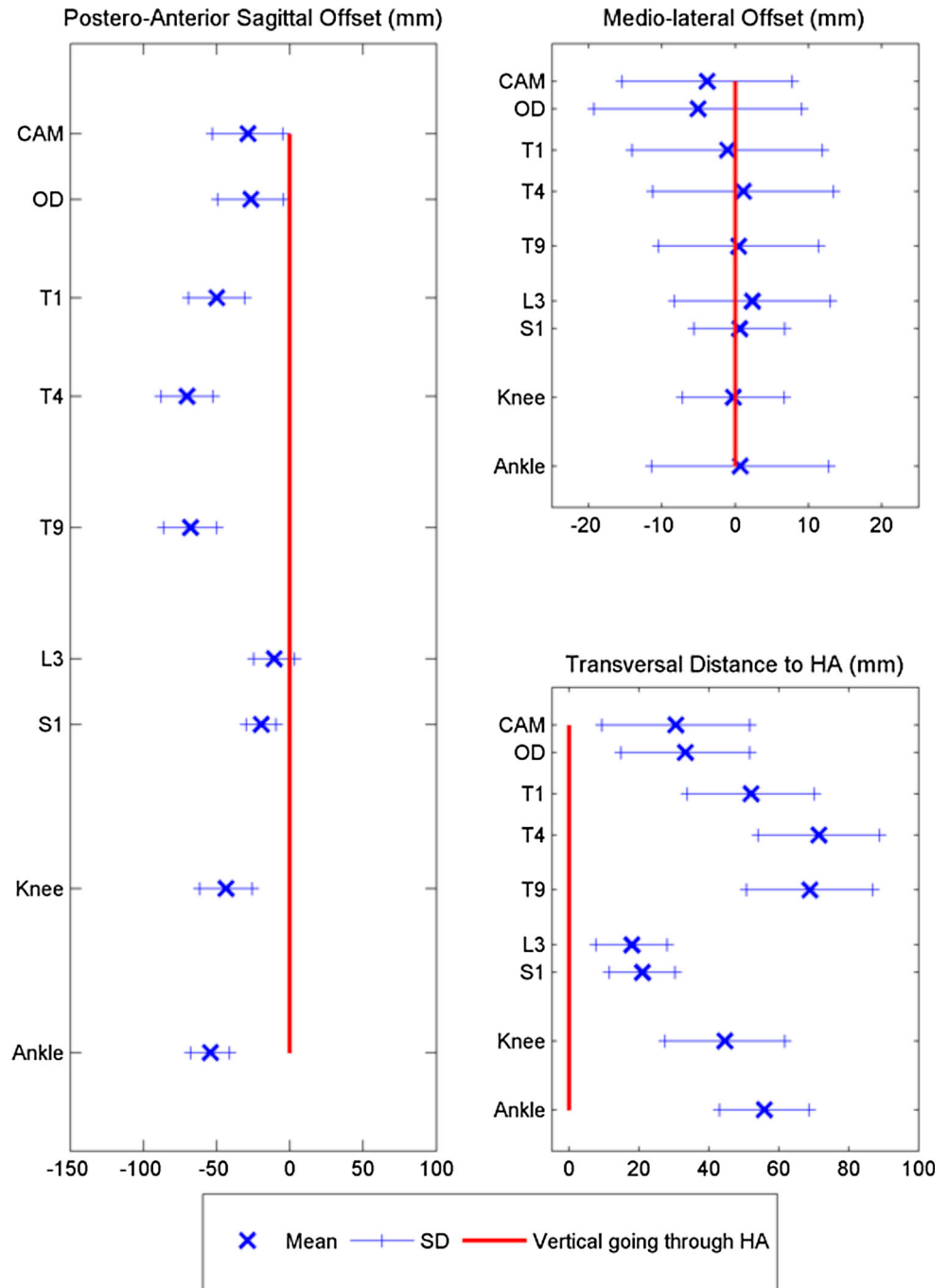
### Global alignment parameters

The inclination of the line joining CAM and HA and the line joining OD and HA are the less variable among subjects (respectively SD = 1.7° and SD = 1.6°). The line with the OD point is less variable between subjects and

more robust when it comes to digitizing the point on the radiographies.

Few studies reported values for inclinations: values similar to those reported in the literature were found for inclinations of the line going through T9 and HA (T9–HA); of the line going through T1 and S1 (T1–S1); of the line going through T1 and HA (T1–HA) and of the least square line going through OD, all the vertebral bodies from C3 to L5 and S1 (Incl\_2) [7, 28]. Another alignment parameter is the T1 pelvic alignment (TPA) reflecting the inclination of the trunk and pelvic retroversion (accounting for both SVA

**Fig. 4** Offsets from the vertical going through the center of the bi-coxofemoral axis (HA) (mean  $\pm 1 \times$  SD)



and PT). Ryan et al. reported a value of TPA less than  $15.9^\circ$  for patients with adult spinal deformities well aligned [29], proposing a surgical target of  $10^\circ$  for TPA. For young asymptomatic adults (well aligned), mean TPA is  $5.3^\circ$  ( $SD = 5.7^\circ$ ), which means that 66 % of the population ranges between  $-0.4^\circ$  and  $11.0^\circ$ . Some have subnormal values, between mean  $-2 \times SD$  and mean  $-1 \times SD$  (respectively between mean  $+1 \times SD$  and mean  $+2 \times SD$ ) which can reach  $-6.1^\circ$  (respectively  $16.7^\circ$ ). This shows that the target set by Ryan et al. [29] could be adjusted to identify abnormalities.

For the global inclinations, the least squared line going through the points CAM, OD, centers of vertebral bodies from C3 to L5 and S1 (Incl\_1 in Table 3) presented an inclination of  $3.1^\circ$  in average ( $SD 1.9^\circ$ ) versus  $3.5^\circ$  in average ( $SD 2.1^\circ$ ) for the second least-squared line (Incl\_2), going through OD, centers of vertebral bodies from C3 to L5 and S1. The line used in Incl\_1 is more vertical and less variable between subjects but the weaker digitization of CAM makes it less robust.

The C7 point can be useful when CAM and/or OD are not visible on the radiographies. The C7-HA inclination is



slightly greater than CAM–HA (4.3° versus 2.9°) and only very slightly more variable (SD: 1.9° versus 1.7°). It will be interesting to investigate whether this parameter is more variable in older subjects.

The CAM–HA or OD–HA parameter will be useful to assess the global alignment taking into account the cervical part of the spine contrary to the SVA and C7–HA parameter. Depending on the use and interpretation, studies could use CAM, OD or C7 points to characterize global alignment with CAM–HA, OD–HA, SVA and C7–HA that appear as complementary parameters. In addition, it will be interesting to further investigate changes for pathological and aging population, in the newly described parameters (CAM–HA and OD–HA) compared to SVA and C7–HA.

CAM and OD points were chosen to account for the head position. Previous studies have focused on other specific points to quantify alignment of the head with the spine and pelvis: such as the sella turcica [13], McGregor line [13], or cranial center of mass (as the midpoint of the nasion-inion line) [11]. Commonly to the current study, all considered points supposed to be close to the true center of mass of the head to quantify its alignment compared to the pelvis. However, in analyzing radiographs, a reliable and accurate but also easy-to-implement method is needed to identify points of interest (particularly when working in a clinical environment). That is why in this study, only points directly identifiable on the 3D model of the spine were considered: for the head, this included only the points CAM and OD. It can be noted that all these studies including this one, concluded on the importance of the position of the head above the pelvis in the global postural alignment [11, 13].

## Offsets

Variability between subjects (SD) was comparable between the angles, measured in the sagittal planes: CAM–HA (SD = 2.1°), OD–HA (SD = 2.0°) and C7–HA (SD = 2.1°). Inter-subject variability was greater for the angle corresponding to SVA: angle with the vertical of the line joining through C7 and <sup>post-sup</sup>S1 (SD = 2.8°). This suggests that the use of the point <sup>post-sup</sup>S1 accounts for the inclination of the pelvis as well in this angle, when compared to the angle C7–HA using the point HA. Comparison of the angles CAM–HA, OD–HA and C7–HA highlighted that, for asymptomatic volunteers, these data variability are similar. It would be particularly interesting to assess changes occurring during aging and/or pathological conditions. Studies' reported offsets used the gravity line as the reference line [10, 25, 30], using a forceplate simultaneously to the X-ray acquisition. Experimental setup did not provided forceplate data, thus we decided to use the vertical going through the center of the bi-coxofemoral axis (HA) as the reference line and not the heels as done in

Schwab et al. [25] as, here, the feet's positions were not found to be consistent enough between all subjects to be used as a reference line. Despite these differences, our values are of the same order of magnitude as the literature's [10, 25, 30]. In addition, it can be noted that offsets of both knees' and ankles' centers were found to be relatively close to HA in the transverse plane (less than 6 cm); this provides a baseline for comparison with older subjects.

## Limitations

One limitation is the non-uniform age distribution: more subjects between 30 and 40 years old might highlight some correlations between all the parameters that were hidden here. Another limitation resides in the position of the subject in the X-ray cabin. Particularly, the position of the hands on the mandibles might have affected the volunteer's posture by shifting backwards the upper body to make room for the arms flexed. In addition, the shift between the feet must be controlled to be consistent between subjects. Monitoring more precisely the patient's position would lead to more reliable results characteristics of the true subject's erected posture.

## Conclusion

In conclusion, a description of the postural alignment in 3D, and in sagittal and frontal planes of the young healthy adult has been reported. As hypothesized, the head is, for each subject, placed above the pelvis (line CAM–HA little variable). In this control group, the spine is globally vertical as the parameter Incl\_1 and Incl\_2 are close to 0°. We described the postural alignment and the geometry of the following segments: spine, pelvis, lower limbs. This study on young healthy adults (18–40 years old) would allow future comparisons for older population.

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## Compliance with ethical standards

**Conflict of interest** Wafa Skalli is the coinventor of the EOS system without direct/personal financial benefit. Her institution received financial support from the ParisTech Chair Program for research on musculoskeletal research.

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